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MEMORANDUM

INVESTIGATION OF THE CHARACTERISTICS OF AN

ACCELERATION-TYPE TAKE-OFF INDICATOR

IN A LARGE JET AIRPLANE

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SUMMARY

The characteristics of a proposed acceleration-type take-off indicator were observed during take-off runs of a large jet airplane. The instrument performed its function satisfactorily. It showed an essentially constant reading, which agreed closely with the predicted value, throughout the take-off except for about the first 135 feet of the ground roll during which the starting windup of the indicator pointer occurred. Although oscillating longitudinal accelerations at the instrument location were as much as ±50 percent of the steady-state acceleration, the instrument showed only small excursions from the mean reading equivalent to not more than ±5 percent of the mean reading and was considered to be satisfactorily readable.

INTRODUCTION

The use of high wing loadings and wings with lower maximum-lift capabilities has resulted in smaller performance margins on existing runways. In addition, increased stopping distances are required in aborted take-offs by jet aircraft which do not have reversed thrust. Therefore, it is becoming increasingly important for a pilot to recognize quickly any deficiency in airplane acceleration during take-off so that the take-off run can be aborted if necessary and the airplane brought to a safe stop.

Losses in airplane take-off performance can occur from loss in thrust, dragging brakes, an increase in rolling or aerodynamic resistance, or meteorological conditions different from those used in the take-off calculations. The Langley Research Center had proposed an instrument to detect such subnormal take-off performance. The operating principles of the proposed instrument, which is basically an accelerometer, and the results of preliminary tests with a simplified

model of the instrument are presented in reference 1. A complete model of the instrument has since been constructed in order to verify the operating principles and to reveal any unexpected problems and limitations associated with this type of take-off performance monitor. Early tests of the instrument in a large jet airplane showed large fluctuations of the instrument pointer that made the indicator unreadable. The dynamic characteristics of the instrument were modified to attenuate the instrument-pointer fluctuations. This report presents the results of tests of the modified instrument in a similar airplane.

INSTRUMENTATION AND TESTING

Take-Off Indicator

The fundamental operating principles of the take-off indicator are completely described in reference 1; hence, only a brief description will be given herein. The take-off indicator (fig. 1) is basically designed to indicate acceleration as this is one of the most direct methods of measuring the take-off performance level of an airplane. However, airplane acceleration, primarily because of the buildup of drag, falls off substantially during take-off. In order to compensate for the fall off in acceleration, the instrument incorporates impact-pressure sensing elements whose output is mechanically added in the proper proportion to the accelerometer output. This compensation results in a constant predictable instrument reading for normal performance of the airplane. For this compensation it is assumed that acceleration during take-off decreases very nearly linearly with dynamic pressure. This assumption has been verified on all airplanes tested including the present one. Figure 2 shows how the acceleration decrement varies with dynamic pressure for this airplane and this plot was used for adjusting the instrument in the tests. Instrument adjustment is made by means of two external knobs. (See fig. 1.) The "W" knob varies the sensitivity of the accelerometer for different airplane weights and maintains at the same time the proper relationship between the accelerometer and dynamic-pressure outputs. Thus, the instrument reading is compensated for acceleration fall-off with speed for any weight condition. Since the instrument reading is proportional to the static excess thrust, an adjustment which accounts for normal variations in thrust with temperature and pressure must be made. An additional adjustment must also be made for variations in rolling friction with airplane weight. These adjustments are made by means of the "D" knob which rotates the dial and reference marker to the position where the pointer should be during normal take-off. Positioning of the reference marker is determined from a chart, as shown in figure 3. Because airplanes have both pitching motions and structural vibrations, it was necessary to develop a damping system and mechanical filter to eliminate these effects from the indications of the earlier

unsatisfactory instrument. A complete description of the fully modified instrument as used in the present tests is given in the appendix.

Instrumentation

The take-off indicator and an airspeed indicator were mounted on a panel rigidly attached to the airplane structure and located to the left of the copilot's instrument panel as shown in figure 4(a). This panel also served as a mount for longitudinal, normal, and transverse Statham acceleration pickups which were used to determine the acceleration environment of the take-off indicator. Their outputs were recorded on a 6-channel oscillograph located on the navigator's table along with the 110-volt 400-cycle power supply as shown in figure 4(b). A 16-millimeter motion-picture camera was mounted about 3 feet back of the take-off and airspeed indicator panel and was used to photograph the indicators during the take-off run. A three-component recording accelerometer (fig. 4(c)), which was used to obtain airplane acceleration, was located about 2 feet forward of the center of gravity used during the tests.

The take-off indicator, Statham acceleration pick-ups, and the three-component accelerometer were lined up horizontally when the airplane attitude was 5° which is the attitude during the take-off run. All the instruments were synchronized by means of a 0.1-second timer. The motion-picture camera was coordinated with the other instruments by recording the time each frame was exposed on the oscillograph.

Tests

Two take-offs were made at a gross weight of 135,000 pounds but only the results of one take-off are presented herein since similar results were obtained with both runs. The chart (fig. 3) was used to obtain the dial setting for the take-off indicator from pressure altitude and temperatures supplied by the navigator's instruments shortly before take-off.

Both take-offs were made from the full-power brake-locked starting position and, when brakes were released, no further braking occurred. A standard take-off airplane configuration was used for both runs with the airplane center of gravity at about 25 percent mean aerodynamic chord.

The take-off for which the results are presented was made with a cross wind of 12 to 20 knots.

RESULTS AND DISCUSSION

Results of the investigation are presented in figures 5 and 6. Time histories of longitudinal and normal accelerations measured during take-off at the take-off indicator position are presented in figure 5 as an indication of the acceleration environment in which the instrument was operating. It is shown that oscillating longitudinal accelerations as large as ±25 percent of the steady-state acceleration were encountered at a frequency of about 1 cycle per second and that accelerations of ±50 percent of the steady-state acceleration occurred at about 7 cycles per second. It will be noted that, 32 seconds after the start of the run, the steady-state acceleration had decreased by about 40 percent of the initial value. Normal-acceleration fluctuations were of considerably greater magnitude than the longitudinal accelerations and at times exceeded ±0.3g. However, normal accelerations should have little effect on the take-off indicator if it is properly alined.

The time history of the take-off indicator reading is shown in figure 6 in terms of degrees of pointer rotation from the preset reference and also in percent of displacement from zero. The time history of airspeed reading is also presented in figure 6. It is shown that the take-off indicator filtered out the greater part of the oscillatory longitudinal accelerations shown in figure 5; thus, the maximum excursion of the needle from the steady-state reading was only about ±5 percent. The instrument indication is considered to be sufficiently steady to provide satisfactory readability. The mean reading of the instrument was constant, as desired, to within about 1 percent throughout the take-off run up to 140 miles per hour; therefore, the material decline of acceleration with increasing speed was satisfactorily compensated for by the acceleration—dynamic-pressure summing mechanism of the instrument. The generally small deviations from the mean reading and the fairly constant mean reading throughout the take-off run were evidence that there was no appreciable variation in pitch attitude during the take-off run inasmuch as the instrument would respond to pitch-attitude changes as well as to longitudinal-acceleration changes. Actual photographic measurements of attitude angle of an identical airplane during take-off showed an oscillating attitude variation of less than 0.4° with a period of 1 to 2 seconds, but no steady-state variation between the beginning and end of the take-off.

Since the instrument has a time constant of approximately $1\frac{1}{2}$ seconds, some time must elapse before any step input is indicated. From the time history of the take-off indicator it is shown that 6 seconds (4 time constants) were required for the instrument to attain final (full scale) indication after brake release at the start of take-off. This lag does not constitute a serious deficiency for an airplane of the type used because the airplane travels only about 135 feet (about 3 percent of the

total take-off ground roll) in this time. During the remainder of the take-off ground roll the time lag would still be of small significance because of the small changes in indication allowable. For example, if a 10-percent decrease in thrust occurs, the indication would show a 7-percent decrease within $1\frac{1}{2}$ seconds.

The mean take-off indicator reading averaged about 3 percent higher than the predicted reading or dial setting. Several factors contributing to this difference are: The installed thrust characteristics of the engine were not available; thus the dial-setting chart (fig. 3) was based on uninstalled engine data and may be somewhat in error. The rolling coefficient of friction was assumed to be 0.02 which may be a little high. The engine settings during take-off were such that a slightly higher than normal thrust was attained. It is possible that, for operational use of the instrument, the dial setting chart would have to be based on tests of several airplanes of the type in which the instrument is to be installed.

Results from previous tests in this airplane indicate that at higher gross weights the magnitude of the oscillating longitudinal accelerations decreased at the take-off indicator station, and subsequently a steadier instrument indication is provided.

CONCLUDING REMARKS

Results of an investigation of the characteristics of an acceleration-type take-off indicator during take-offs in a large jet airplane show that the instrument indication is sufficiently steady to provide satisfactory readability. The first 6 seconds of a total of 32 seconds needed for the take-off roll was required for the instrument to show an essentially constant reading throughout the remainder of the ground roll. This 6-second lag was not considered to be a serious deficiency because the airplane traveled only 135 feet or about 3 percent of the ground roll during this time. Although longitudinal acceleration oscillations at the instrument position amounted to as much as ±50 percent of the steady-state acceleration, the instrument showed only a small excursion from the mean reading which was equivalent to not more than ±5 percent of the mean reading. The mean reading of the instrument agreed closely with the predicted reading. Therefore, it is concluded that an instrument using the basic theoretical principles employed would be satisfactory as a take-off aid.

Langley Research Center,
    National Aeronautics and Space Administration,
        Langley Field, Va., December 9, 1958.

APPENDIX

DESCRIPTION OF ACCELERATION-TYPE TAKE-OFF INDICATOR

Design Considerations

A prototype take-off monitor was built primarily to see whether the instrument design would give indications in accord with the theoretical equations and secondarily to uncover the latent defects in the design. No external weight adjustments were used on this instrument and a parallel-plate open-type, viscous-shear damper was employed to attenuate the response of the accelerometer to undesirable frequencies. The natural frequency of the mass spring system was calculated to be about 5 cycles per second and the damping system was set up to give critical damping. Initial tests made in single-engine jet airplanes proved that the instrument responded according to theory and that an instrument of this type was practical for use. However, during later tests, larger pointer oscillations ($\pm 1/4$ full scale) occurred at 1.5 cycles per second and 3.6 cycles per second because of intermittent damper failure which made the instrument unreadable. Laboratory tests made on a pendulum rig and vibrating beam indicated that the damping system failed under short-time cycling due to separation of the damping fluid under prolonged shearing stress. Over long periods of time, too, the fluid tended to creep out from between the damping plates and loss of damping or reduced damping resulted. The dynamic tests showed the natural frequency of the instrument to be about 3.6 cycles per second.

Tests made on the pointer system indicated that undesirable pointer oscillations would be minimized if the angular inertia of the pointer could be reduced. A balsa pointer tapered in thickness from hub to tip gave the desired results. A low-rigidity coupling between drive shaft and pointer was tested to see whether it would filter out higher frequency inputs to the pointer. It proved to be successful. The prototype instrument was then modified to incorporate the following:

(a) An external weight-adjusting and indicating feature.

(b) A low angular inertia pointer.

(c) A low-rigidity pointer-drive shaft coupling for further attenuating undesirable pointer oscillations.

(d) A closed fluid damping system.

The weight-adjusting feature may be seen in figure 7. In order to obtain a closed damping system damping fluid was placed within two matched diaphragms having the same effective area. A reservoir bellows accomodates fluid volume changes due to temperature. Damping is accomplished by mechanical fluid displacement through a small annular space between the push-pull rod operating the diaphragms and the diaphragm support tube. One diaphragm is exposed to static pressure and the other enclosed in a sealed can is exposed to total pressure. The two diaphragms are connected by the push-pull rod so that the displacement of the two diaphragms is proportional only to impact pressure. Matched diaphragms with equal effective areas were chosen and the instrument was modified to incorporate these features.

The damping system was again found to be faulty because the diaphragms distorted and did not force the damping fluid through the annular cylindrical space. In order to correct this defect, the damping system was revised to include a mechanical fluid displacement damping piston and cylinder. This system is shown in figure 7. The instrument was then mounted on a pendulum test rig and its measured frequency response is shown in figure 8.

The full scale of the instrument is about 360° which corresponds to about 0.2g on the test airplane. This indication would also be obtained if the instrument was inclined approximately 12°. Inclination of the instrument in pitch may occur due to faulty installation or changes in inclination of the airplane's longitudinal axis prior to take-off. For example, a 2° inclination of the instrument would cause a zero shift amounting to approximately 17 percent of the full scale of the instrument. In order to eliminate the effect of these shifts, the instrument zero is set immediately before take-off. The zero-shift adjustment was made possible by insuring that the calibration curve of the instrument was adequately linear and this was accomplished by the adjustment of mechanical linkages within the instrument when it was calibrated.

Design of Take-Off Indicator

A description of the fully modified take-off monitor as used in the present tests follows (numbers refer to specific components of indicator shown in fig. 7):

A mass ⑳ (fig. 7) is fixed to a shaft by two slide bars ⑩ which allow the mass to be moved closer or farther from the shaft axis changing its effective moment. Two identical diaphragms ⑫, mounted in tandem, are connected to the same shaft by means of a link ⑪. The diaphragms thus become the spring system for the mass; and the whole

system becomes the acceleration-sensing element. One of the diaphragms is exposed to the static pressure which enters the instrument case through the static-pressure inlet ⑱ . The other diaphragm, is exposed to total pressure which enters through the total-pressure inlet ⑰ and continues on into the total-pressure sealed can ⑯. The two diaphragms each with the same effective area are connected by a push-pull rod in a manner which eliminates the effects of the static pressure. Diaphragm deflections, therefore, are produced only by the impact pressure and produce shaft rotation through the link and pin coupling in the same direction (additive with) the acceleration sensing unit. Shaft rotation produced by mass or diaphragm deflections imparts angular displacement to the push-pull rod ⑥. The push-pull rod, in turn, engages and drives a fork ⑤ which is staked to the lower sector ④. The lower sector meshes with the lower sector pinion shaft which turns almost 360° (full scale) for 0.04-inch mass motion. A small cylinder half of which is a magnet and the other half brass (magnetic coupling on pointer system) ㉙ turns with the lower sector pinion shaft. The pointer ③ is driven through this magnetic coupling of low rigidity which filters out undesirable pointer oscillation.

Different airplane weights are compensated for by varying the mass moment arm. This variation is accomplished by means of the weight adjusting knob ㉗ . By pushing the knob in, the weight engaging mechanism ㉑ and the clutch ㉒ are engaged. Turning the knob produces rotation in a fixed screw which moves the mass along its slide bars and produces a larger or smaller mass moment arm. A weight index ⑧ is fastened to the mass. When the weight index knob is pushed in, the indicator return sector moves in the direction of the small diameter of the cam ㉔ by force from the engaging spring ㉖ . At the same time the sector which is meshed with the weight indicating pinion causes it to turn. The weight indicating index ⑧ which is staked to the pinion is thus forced against the weight indicating finger ⑨. As the weight indicator pointer ㉘ is press fitted to the pinion above the weight indicator dial (inner dial), it indicates airplane weight settings. The outer dial is made movable and turns concentrically about the fixed weight indicator dial. The dial can thus be rotated to compensate for changes of engine thrust caused by changes in ambient temperature and pressure. The dial has a sector, painted yellow, which is 7 percent of the indicated full scale of the pointer. At the right edge of the sector is a white arrow. For any given setting, if the airplane is operating normally at take-off, the pointer will come up to the arrow and remain there. If the pointer falls to the left edge of the sector 10 percent more than normal

runway length will be required. If it falls within the sector, propor-
tionally less than 10 percent additional runway length will be required.
If it falls out of the sector to the left and remains there, the take-
off on a critical-length runway should probably be aborted. Temperature
and pressure compensation are made by consulting a chart similar to that
of figure 3 which gives a value in percent of rated thrust. Just prior
to take-off the dial knob (7) is turned until this percent value of
thrust (which is marked on the outer dial) appears under the small white
pointer tip. This movement changes the relative position of the sector
and compensation is made.

Damping is accomplished by means of a fluid displacement damper on
the mass system and a magnetic damper and magnetic coupling on the pointer
system. The diaphragms, the diaphragm-connecting support tube, and the
damper cylinder (14) are filled with fluid of the proper viscosity to
give required damping. The mass motion is transmitted through the shaft
to the push-pull rod which connects the diaphragms. The damper cylinder
is fixed to the movable side of the diaphragm and is attached to the
push-pull rod. The damping piston (15) is attached to the diaphragm
support tube and is immovable. Mass deflections, therefore, produce
diaphragm deflections and also damper cylinder deflections about a fixed
damping piston. The damping fluid is forced through a 0.003-inch annular
clearance between the damper cylinder and piston producing the damping
on the mass. Three diaphragm bleed holes (13) lie within the total-
pressure diaphragm and are drilled through the diaphragm support tube.
These bleed holes allow the volume of fluid which is displaced from the
compressed diaphragm to flow to the other diaphragm which is expanded.
An expansion bellows (19) accomodates changes in fluid volume due to
temperature changes. The fluid system is self-correcting against pres-
sure changes.

The pointer is made of balsa to reduce its inertia and angular
momentum. It is magnetically coupled to the mass to reduce the pointer
oscillation further. An aluminum disk (2) fixed on the pointer shaft
rotates between two closely spaced fixed magnets (1) to produce magnetic
damping. The coupling magnet (a cylinder that is half magnet and half
brass) ensures that the same pointer end will return to its proper posi-
tion. The weight of the complete instrument is 3 pounds. Its operation
is completely mechanical and it requires no electrical connections or
power supplies.

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REFERENCE

1. Morris, Garland J., and Lina, Lindsay J.: Description and Preliminary
   Flight Investigation of an Instrument for Detecting Subnormal Accel-
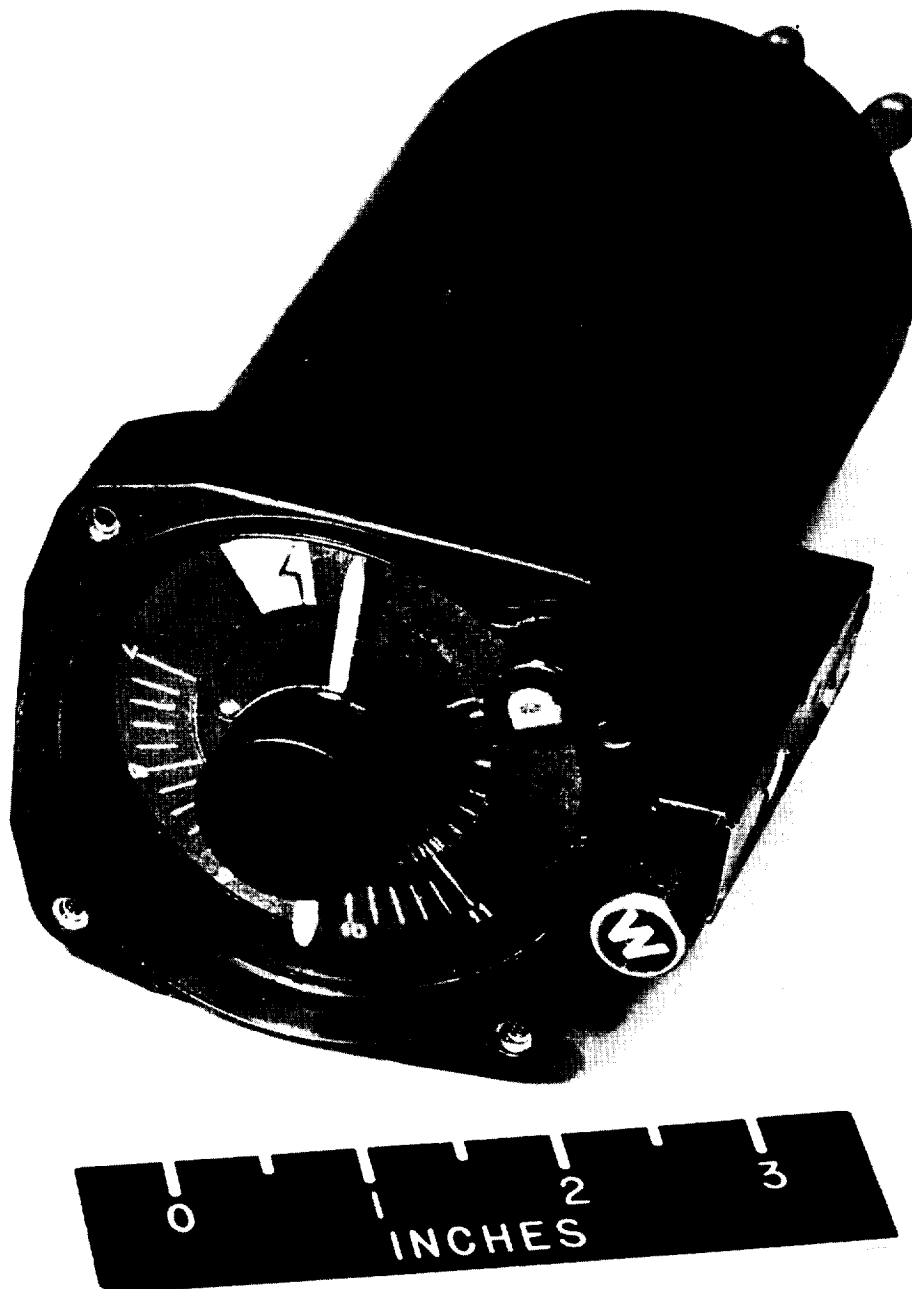   eration During Take-Off. NACA TN 3252, 1954.

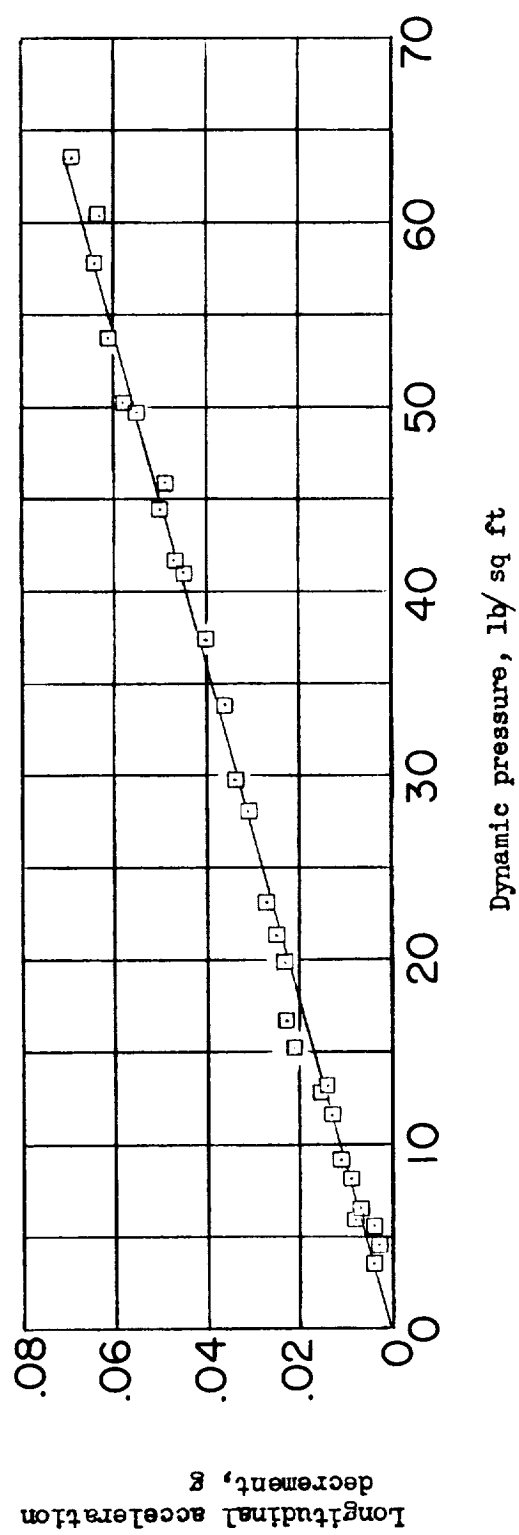Figure 1.- Top right view of take-off indicator.   L-57-3957

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Figure 2.- Typical take-off acceleration of a large jet airplane. Weight, 160,000 lb; temperature, 82° F; pressure altitude, 100 ft.

Instructions

1. Engage "W" knob by pushing in and set small indicator hand to take-off weight. Disengage knob by pulling out.

2. Obtain dial setting from chart: from temperature go horizontally to pressure altitude, then vertically to take-off weight, then parallel to slant lines to "Dial Setting" scale. Sample problem indicated by dashed line. Read value and adjust indicator dial with "D" knob so that number corresponding to "Dial Setting" value is under lower tip of large indicator hand.

3. After turning onto runway for take-off and with engines at low or idling thrust, check dial setting and reset if necessary.

4. With engines at full throttle and brakes fully released, indicator hand should swing around to alinement with arrow in yellow sector and remain there until nose-wheel lift-off.
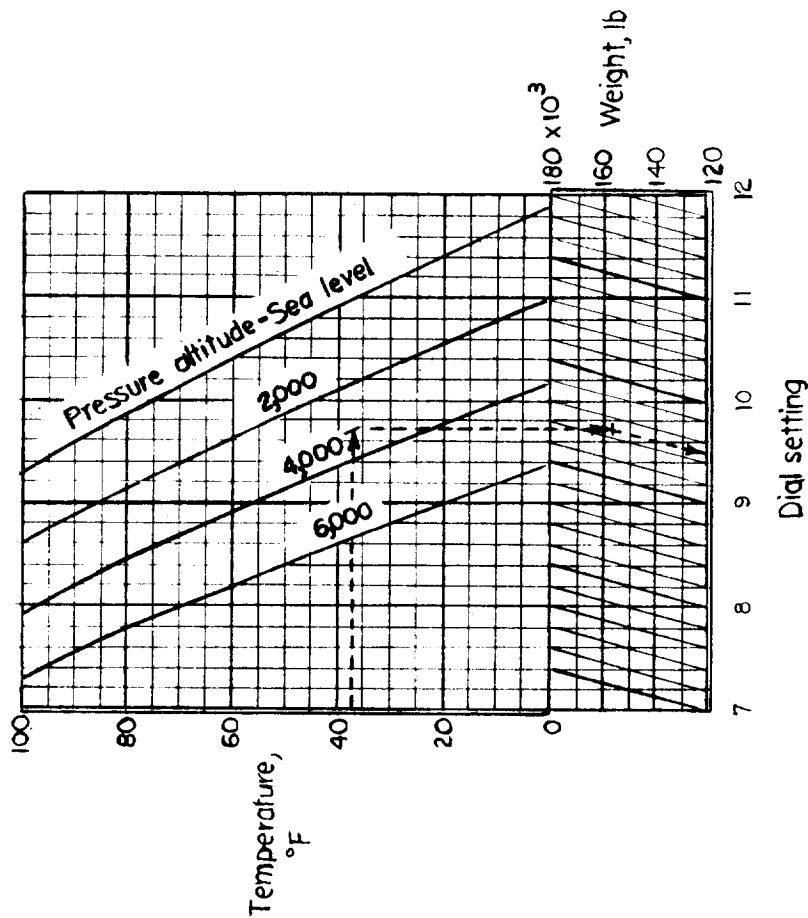
Figure 3.- Take-off indicator chart and instructions.

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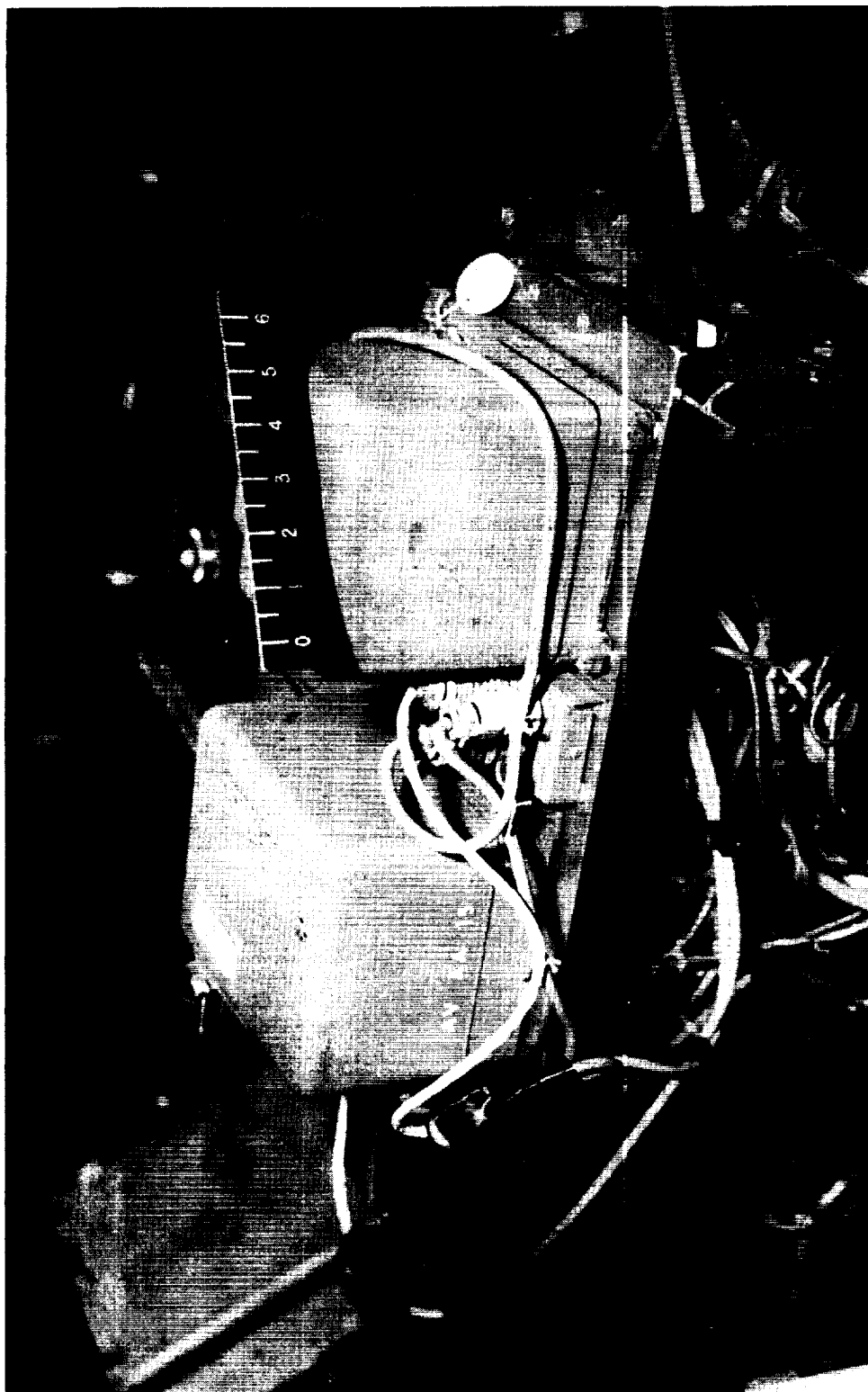(a) Take-off indicator and airspeed indicator. L-58-2226

Figure 4.- Installation of instruments in airplane.
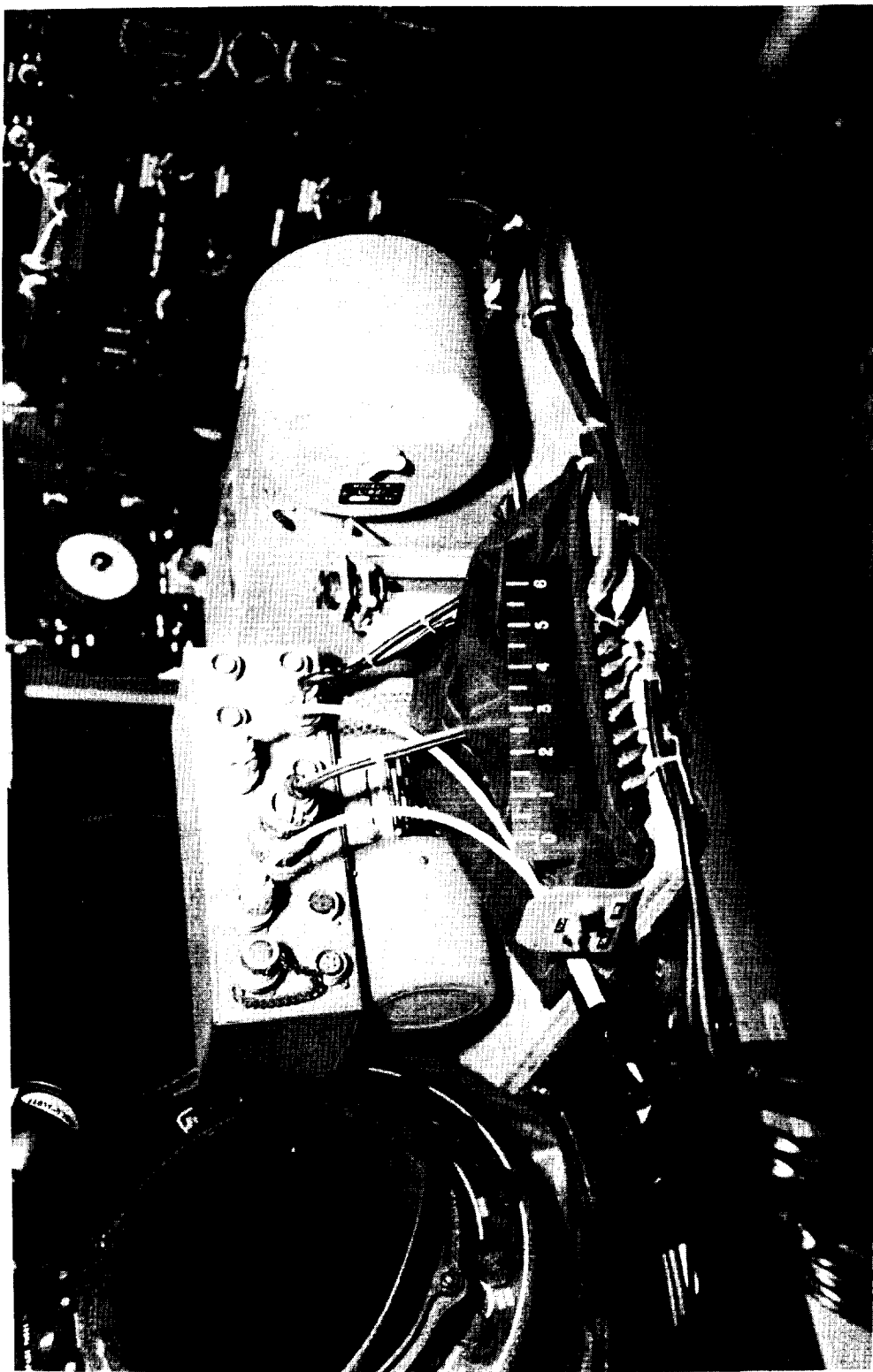
(b) Oscillograph and power supply.   L-58-2224

Figure 4.- Continued.

(c) Accelerometer.
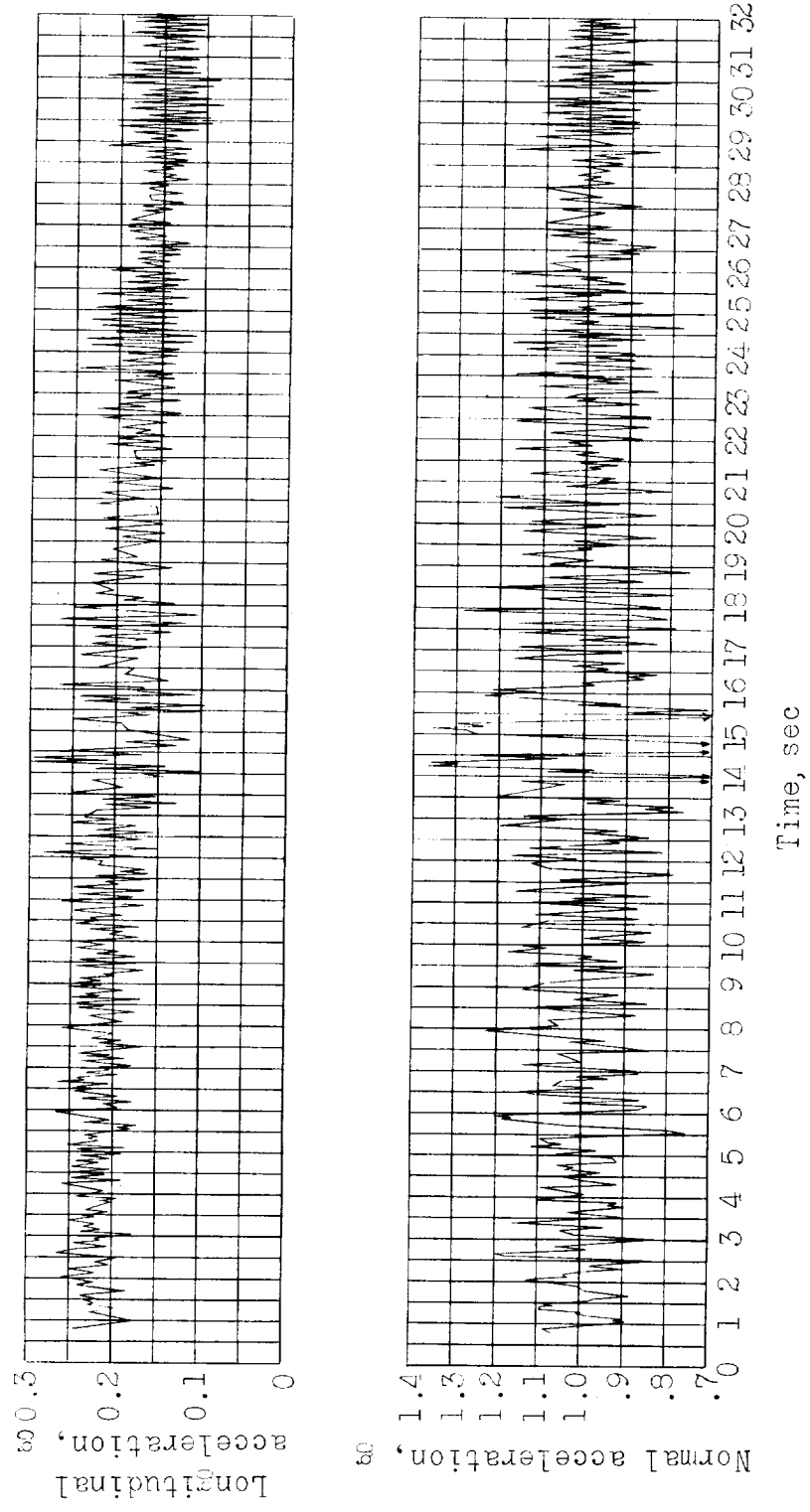
L-58-2222

Figure 4.- Concluded.

Figure 5.- Time histories of longitudinal and normal accelerations at take-off indicator position.
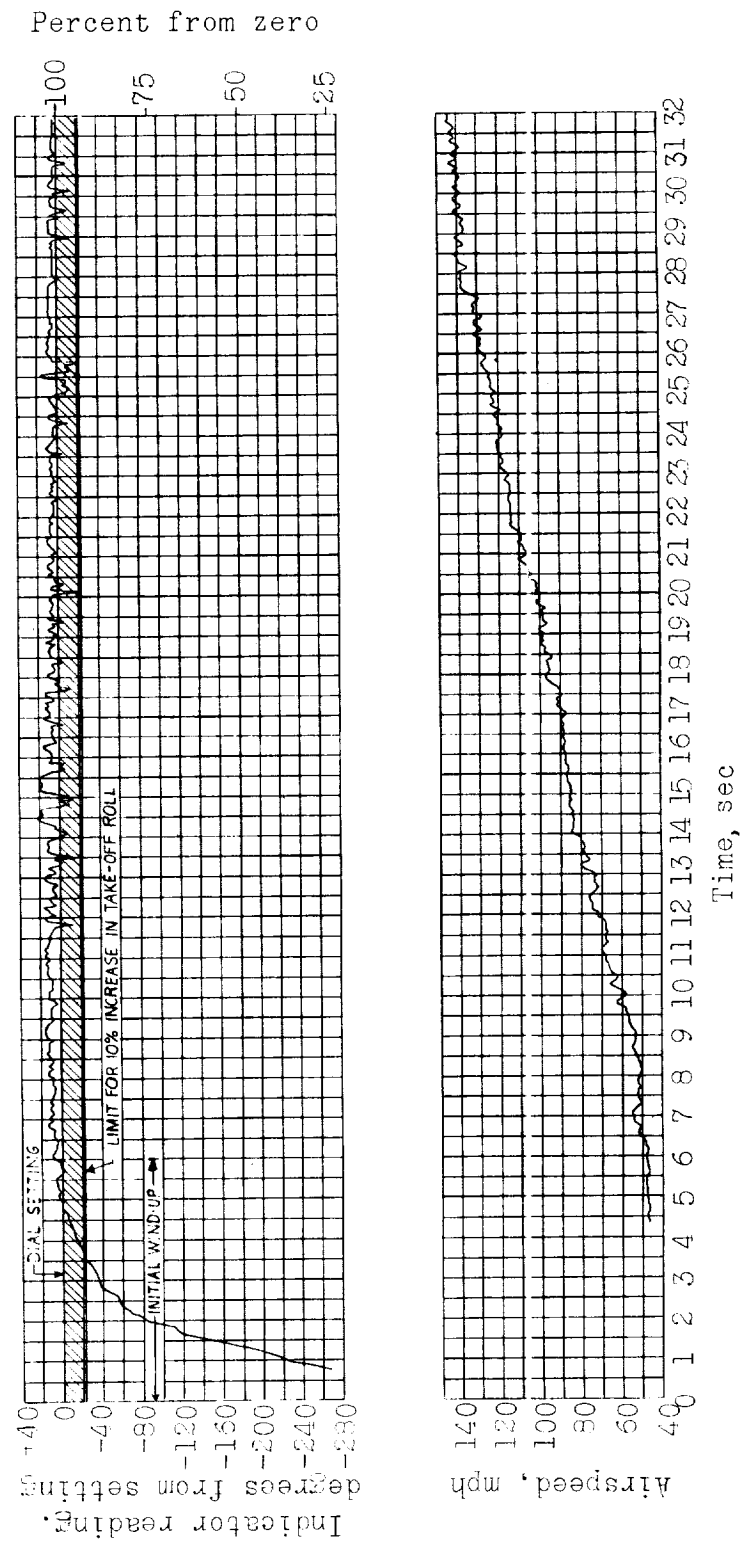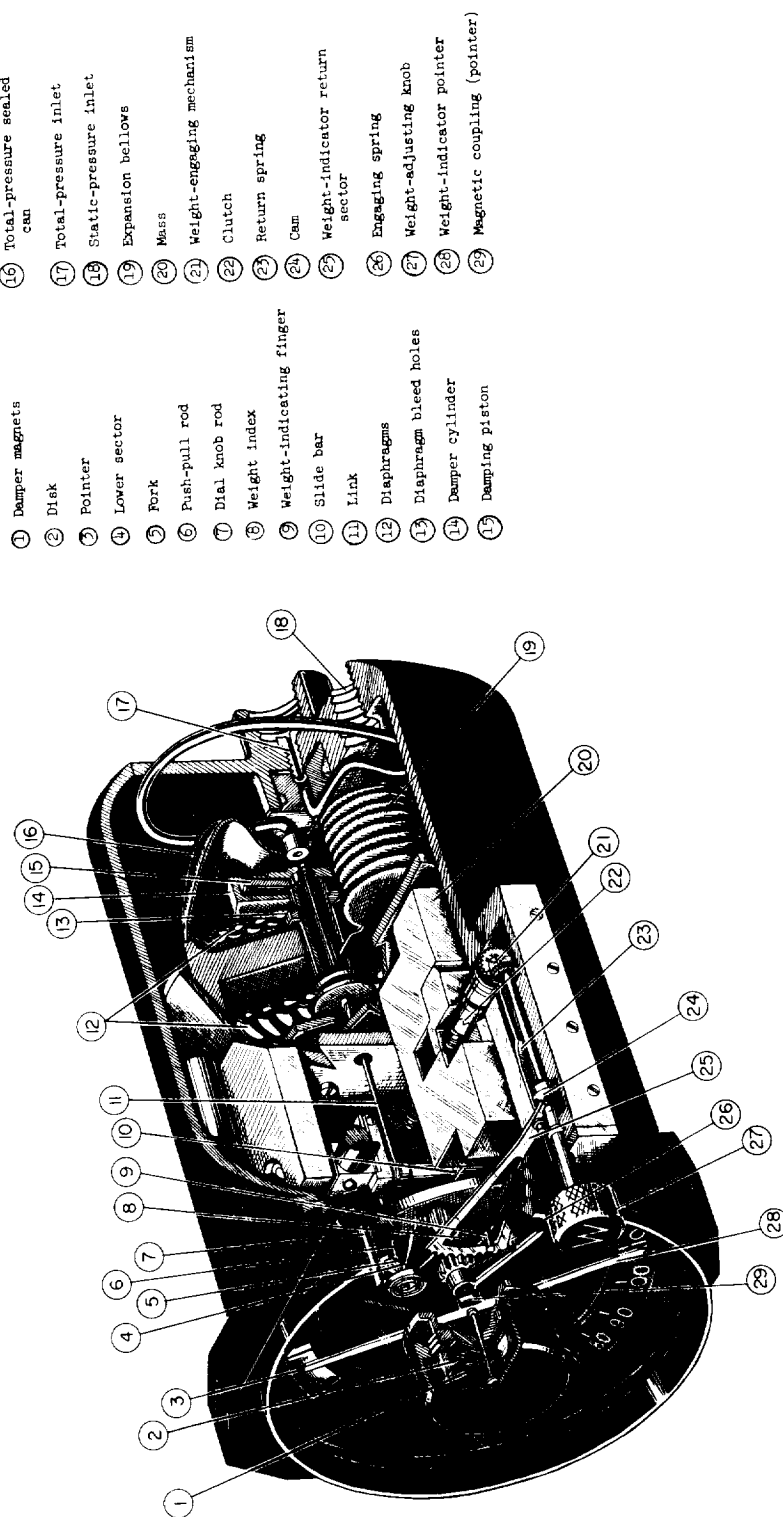
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Figure 6.- Time histories of take-off indicator readings and airspeed.

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1. Damper magnets
2. Disk
3. Pointer
4. Lower sector
5. Fork
6. Push-pull rod
7. Dial knob rod
8. Weight index
9. Weight-indicating finger
10. Slide bar
11. Link
12. Diaphragms
13. Diaphragm bleed holes
14. Damper cylinder
15. Damping piston

16. Total-pressure sealed can
17. Total-pressure inlet
18. Static-pressure inlet
19. Expansion bellows
20. Mass
21. Weight-engaging mechanism
22. Clutch
23. Return spring
24. Cam
25. Weight-indicator return sector
26. Engaging spring
27. Weight-adjusting knob
28. Weight-indicator pointer
29. Magnetic coupling (pointer)

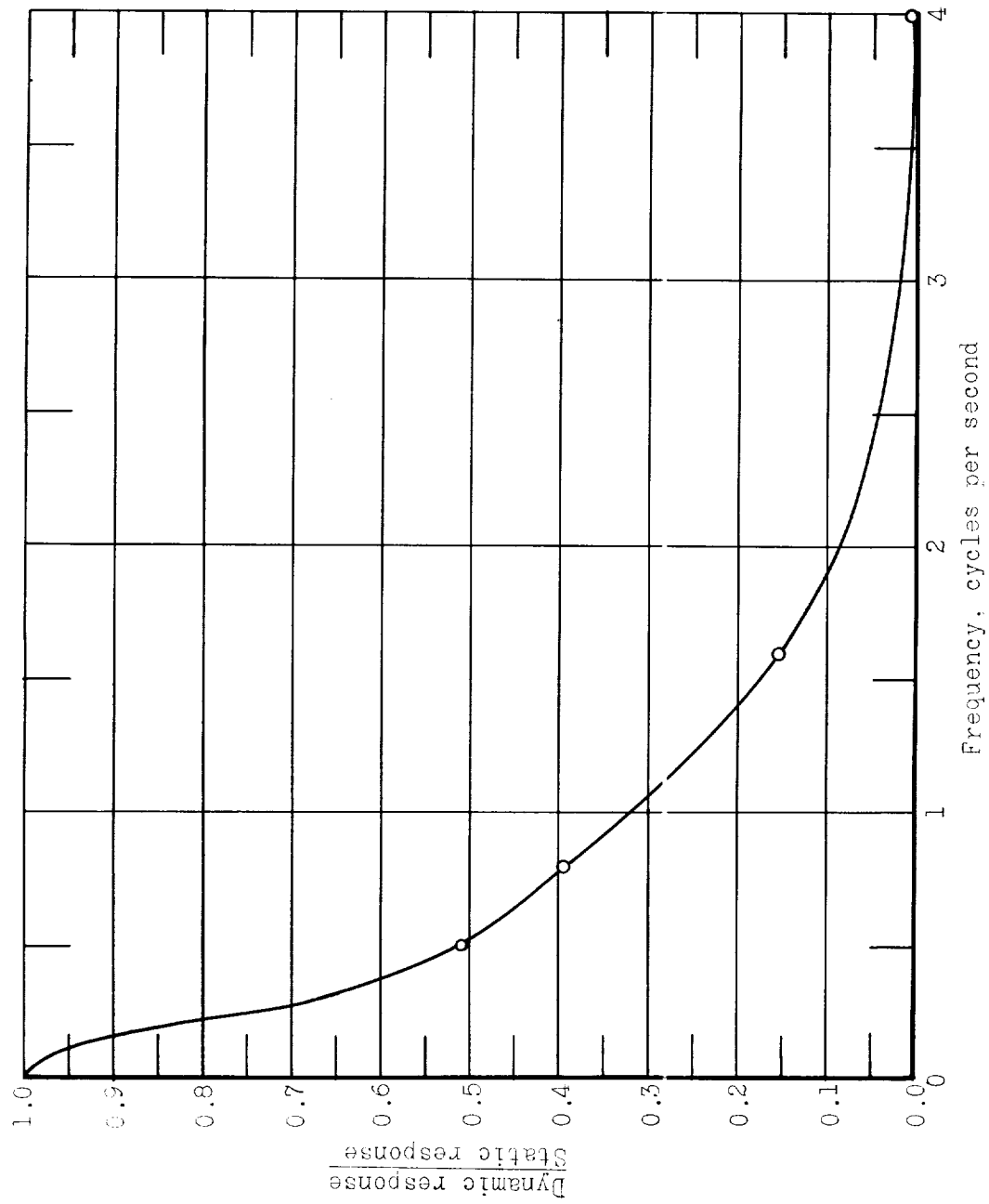Figure 7.- Illustrative arrangement of take-off indicator.

Figure 8.- Frequency response of the fully modified take-off monitor as used on the present tests.